Modelling of Reflectivity Patterns from Artificial Defects

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Abstract: It is well known that the major part of ultrasonic inspection procedure is the evaluation and interpretation of the echo indications. Differentiation of echo's resulting from component geometry and those reflected from a defect is essential to assess the quality and reliability of the component.
In the case of isotropic materials, location and sizing of the defect employing simple geometrical equations is only possible for components, which possess simple geometries. If various reflections and reflectors have to be considered the interpretation of echo indications becomes more difficult.
Under such circumstances, B- or C-scans as well as SAFT reconstruction techniques can be used successfully. In order to understand and overcome signal interpretation problems, experimental results need to be supplemented by wave propagation models, which may be employed to aid visualise specific defects.
The numerical procedure for modelling reflectivity behaviour is based on the Huygen's principle and additionally takes into consideration physical elastodynamics on the boundaries. In the second step various conventional visualisation techniques (mapping) for evaluation are generated and compared.

Introduction and background

We have to remember, that the generation of an echo signal is a complex procedure. The signal is influenced by the probe, the material and the flaw or reflector itself. Large amounts of data result, in particular from automated ultrasonic testing. In order to produce results which facilitate fast interpretation, evaluation procedures often require ultrasound imaging techniques. In this paper examples are shown based on simulated data on how to obtain advantageous picture-like representations or images, when different probes, reflectors and evaluation techniques are used.

Simple pulse echo signals

A probe has a sound field with an extended divergence if it is small in proportion to the wavelength. Such probes can receive echoes from a small point reflector without its own directivity in a wide angle (figure 1). The A-scan is the base representation in ultrasonic NDT showing the echo height in dependence of the transmission time. The transmission time can be converted directly into the distance between the reflector and the probe if the sound velocity is known (distance adjustment). The echo height is proportional to the square of the sound pressure at the reflector and to the reflective capability of the reflector. Consecutive A-scans can be lined up depending on the probe position to built an B-scan. The echo height is shown with brightness or color in B-scans. The B-scan shows the echo dynamic by moving the probe and can be helpful in localizing the reflector.

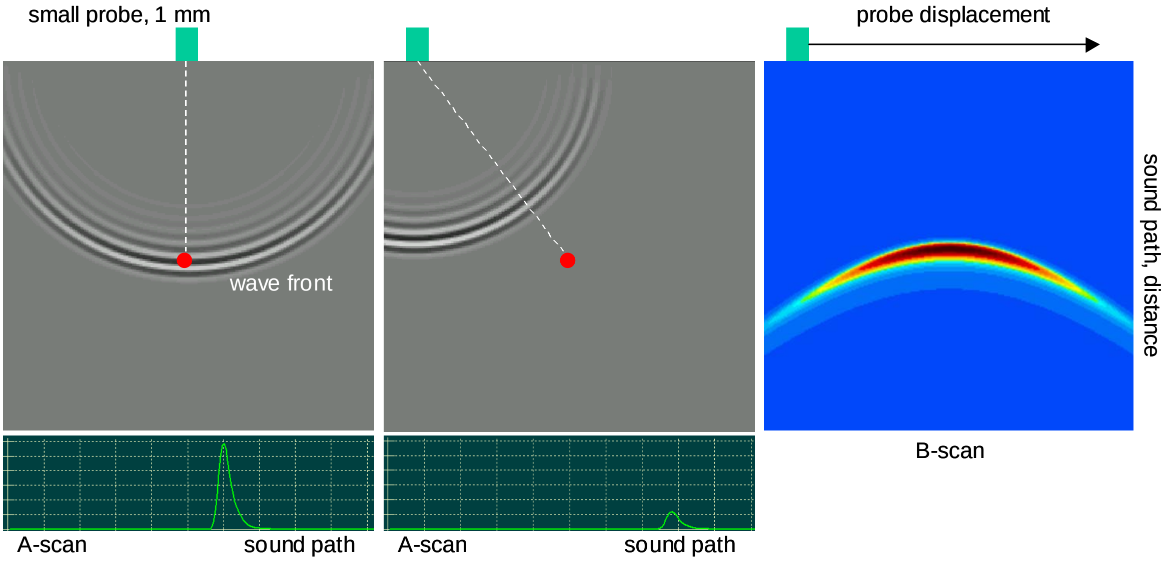

Fig. 1 echo of a point reflector detected by a small probe

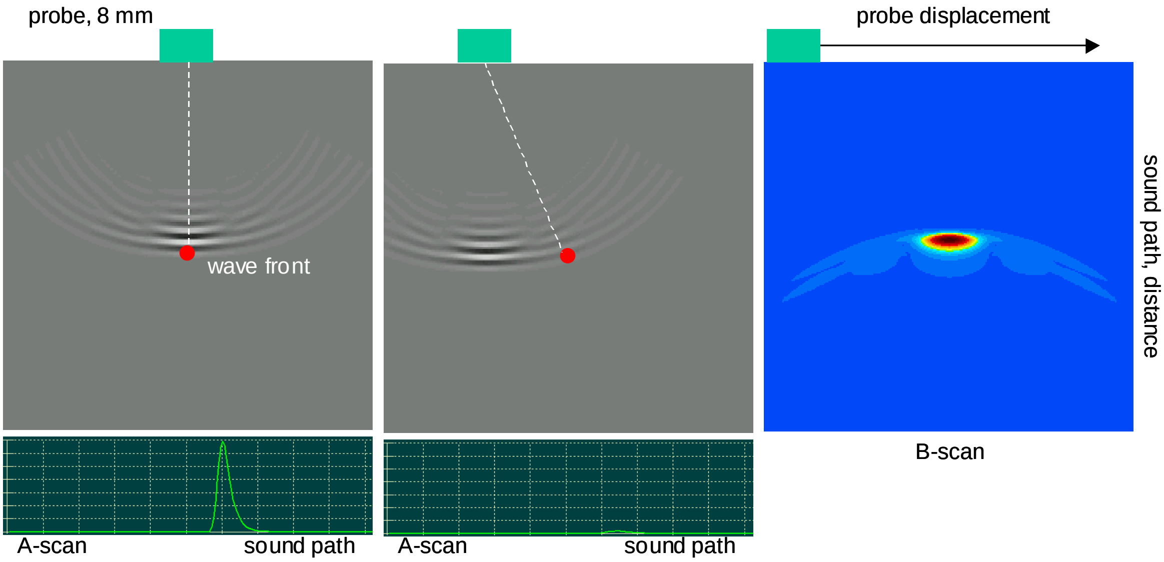

Fig 2 echo of a point reflector, reflector distance in near field length

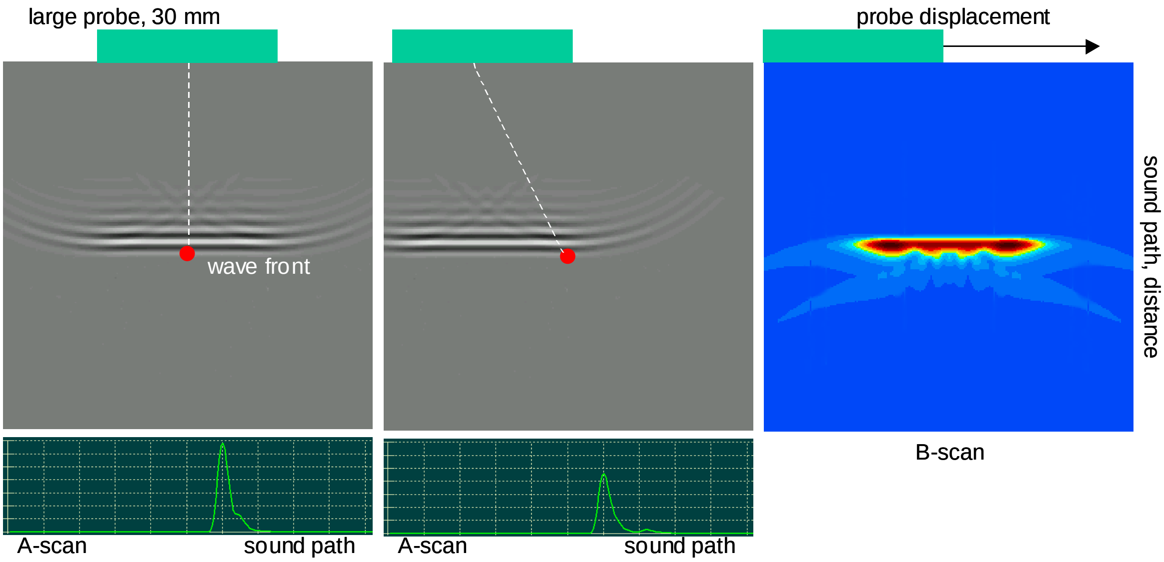

Fig. 3 echo of a point reflector detected by a large probe

If the probe is moved parallel to the plane surface as in figure 1, the typical hyperbolic shape can be seen in the B-scan generated by the distance dependence. The B-scan representation is determined by the shape of sound field of the probe and the small reflector. With plane crystals the smallest representation originates if the reflector is at the nearfield length (figure 2). Smaller or larger crystals have a larger sound field at the location of the reflector (see figure 1 and 3). The sound field can be restricted by focusing to improve the resolution of the B-scan (figure 4). If the aperture is increased (by increasing the size of the crystal in proportion to the wavelength), the centre of focus becomes smaller. We achieve the best image-like representation of the reflector in the B-scan, if the reflector is at the focal distance.

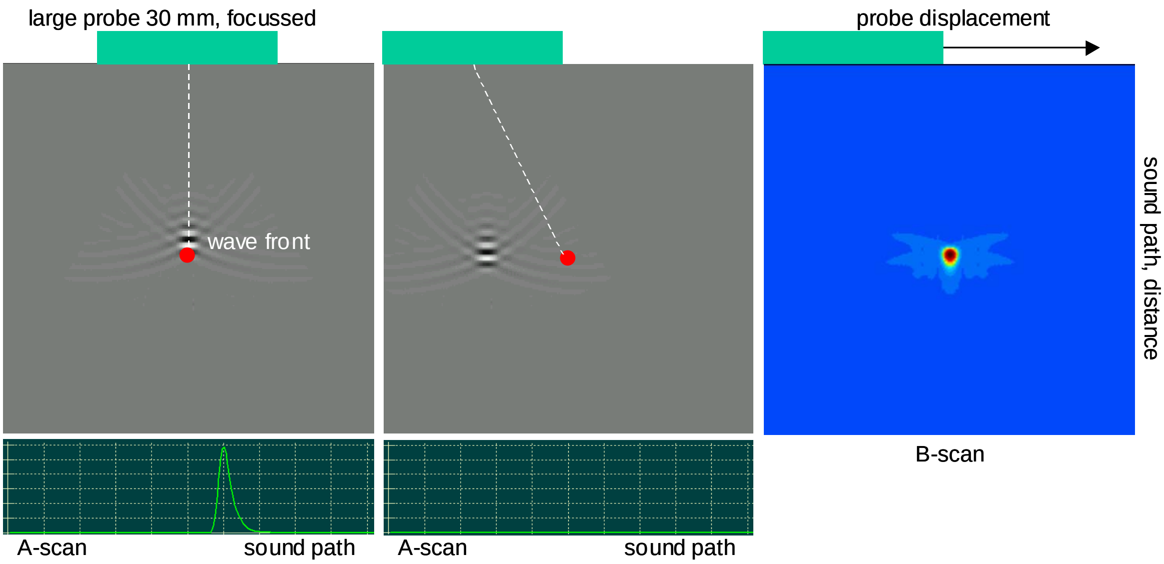

Fig 4 echo of a point reflector detected by a focussed probe

SAFT

The SAFT (**S**ynthetic **A**perture **F**ocusing **T**echnique) is a virtual focusing method using a mathematical algorithm that combines all the raw echo data so that it can be analysed afterwards. Principle (simple version): A small probe sends spheric wave fronts over a large angle, the probe is moved in small steps which are small enough to provide a consistent image and the RF echo signal is recorded. The whole probe movement determines the size of the synthetic aperture. The true position of the reflector is located where the sound paths correspond to the geometrical distances between the probe and the reflector as shown in figure 5. The function of the distance is a hyperbola as identified in figure 1. A simple SAFT-reconstruction can be generated by summation of the RF echo signals (t_0) for every image point. t_0 is the time the echo requires to return to the probe. If an image point contains information on the position of a reflector, then the summation will grow with the number of the echoes from different probe positions on account of the time (and phase) equality. For other image points the phase changes and the sum strives against zero because we summarize harmonic functions with randomised phases.

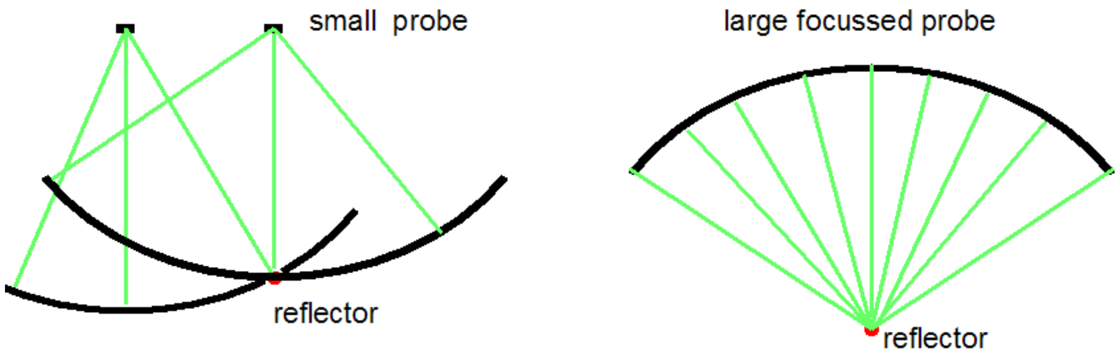

Fig 5 point reflector in a large sound field or in a focussed sound field

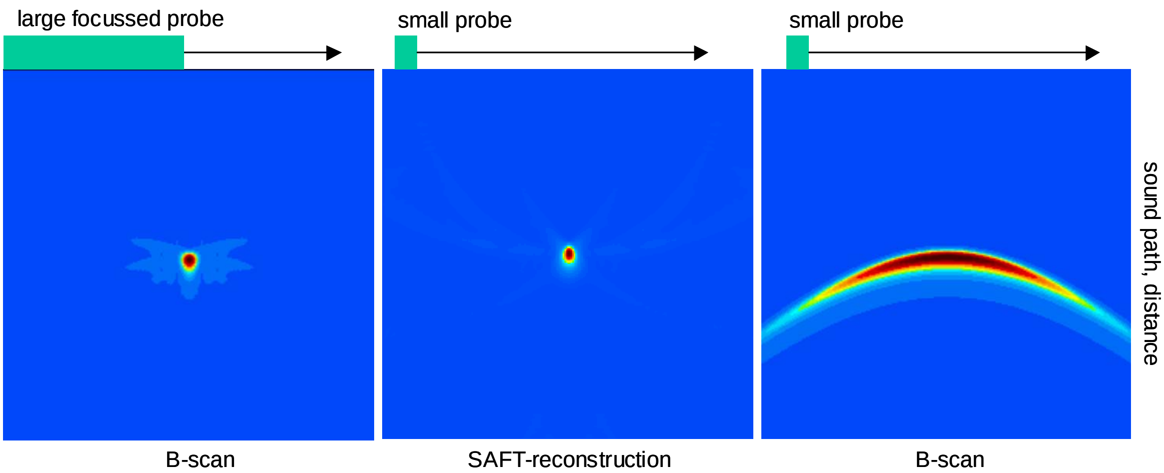

Fig 6 comparison of B-scan and SAFT-reconstruction

The SAFT-reconstruction and the B-scan with the focused probe can generate similar results as shown in figure 5. With the focused sound field good local resolution can be reached only in the vicinity of the focus distance, where the sound bundle is restricted.

Deliberations concerning testing techniques

The application of the inspection determines the testing technique e.g. the choice of the probes, the frequency and the measuring point distance etc.. Flaw detection techniques requires certain compromises to be made in regard to where flaws have a high probability of detection with a given reflectivity (e.g., KSR 2) also that a sufficient signal to noise ratio (→ choice of frequency and probe size) is present, in addition to the fact that inspection time should be short (→ measuring point distance). The assessment of the echo occurs e.g. with the DGS-method (german AVG-Methode) which enables equivalent flaw sizes to be determined. An analysis technique should for instance answer questions in relation to the actual flaw size, the form or the distance to the surface. Therefore a testing technique is needed providing a high resolution, which means using a suitable focusing technique and small measuring point distance in combination with a manipulation system that is precise enough. Flaw detection and analysis techniques set different basic requirements on the testing system. A focus probe requires a small measuring point distance that increases the inspection time however the high resolution is limited to the focus area. A very small probe, that is ideal for the SAFT evaluation, delivers small echo heights and bad signal to noise ratios. These echo signals are poor without using SAFT. Nevertheless, it is economically desirable if both demands can be fulfilled with the same hardware.

The phased array technique offers several possibilities at this point to fulfil the contradictory requirements of detecting and analysis inspection. The sound field of a phased array probe can be skewed and focused at different depths. In addition, it is possible to vary the actual crystal size, while the number of the active array elements is changed. In the following some examples are shown.

"Images" of three reflectors

To obtain a high resolution using each focusing technique requires a large aperture (whether real or synthetic) that means, it must be possible to send and to receive sound within a large angle interval. In addition, plane flaws can only be clearly identified, if it's posssible to receive the echo in the direction of the reflection. The surface of the flaw must be hit roughly vertically by using the pulse/echo technique.

The following representations shows B-sans and SAFT-reconstructions of two rectangles and a cylinder (at 30-mm depth). Real flaw size (black) is inserted in the second row in the figures in each case. The echoes were calculated for surface scans (-30 to + to 30 mms) with different probes in pulse/echo techique. (longitudinal waves $\lambda = 2$ mm, dimension of each single picture area is 60 x 60 mm^2).

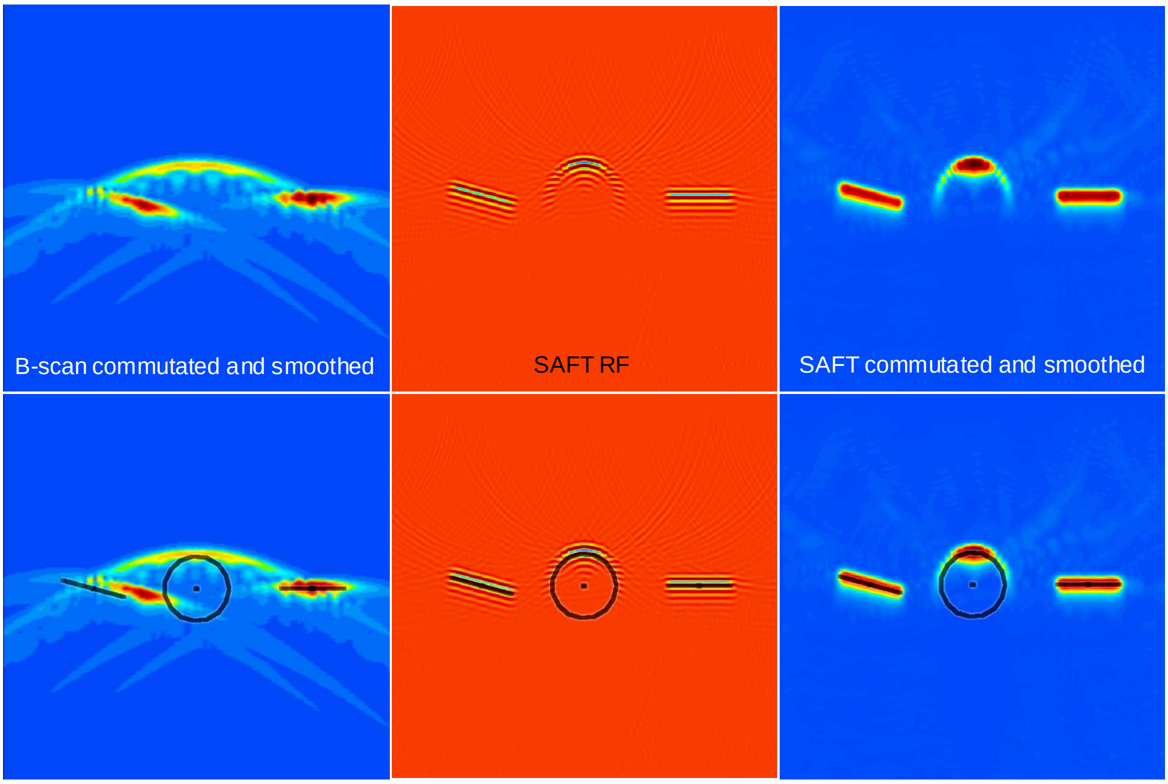

Fig. 7 SAFT-reconstruction and B-scan with pulse-echo signals of a small probe

In figure 7, a one mm large crystal was used. It has the largest divergence possible, the best case scenario for SAFT-reconstruction. The reconstruction shows similarities to an image for all regions of the flaw surfaces where the reflected signal was directly received. The B-scan is less clearly defined.

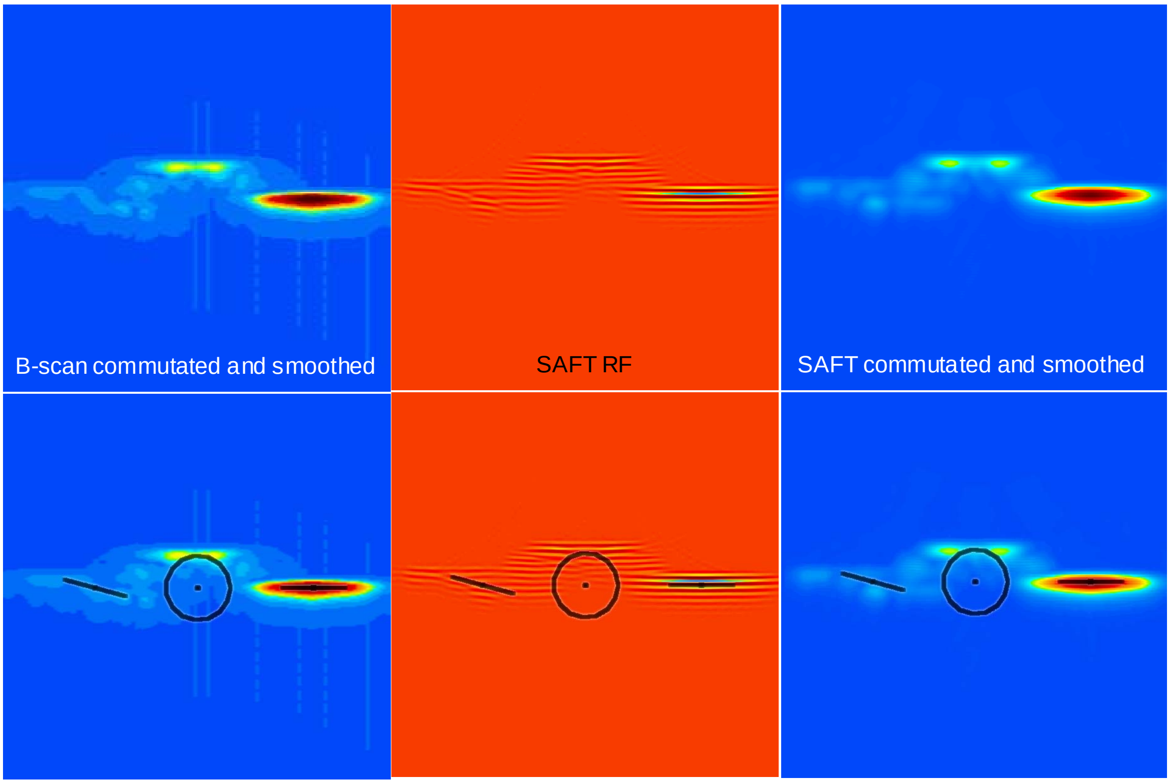

Fig. 8 SAFT-reconstruction and B-scan with pulse-echo signals of a normal sized probe, = 0°

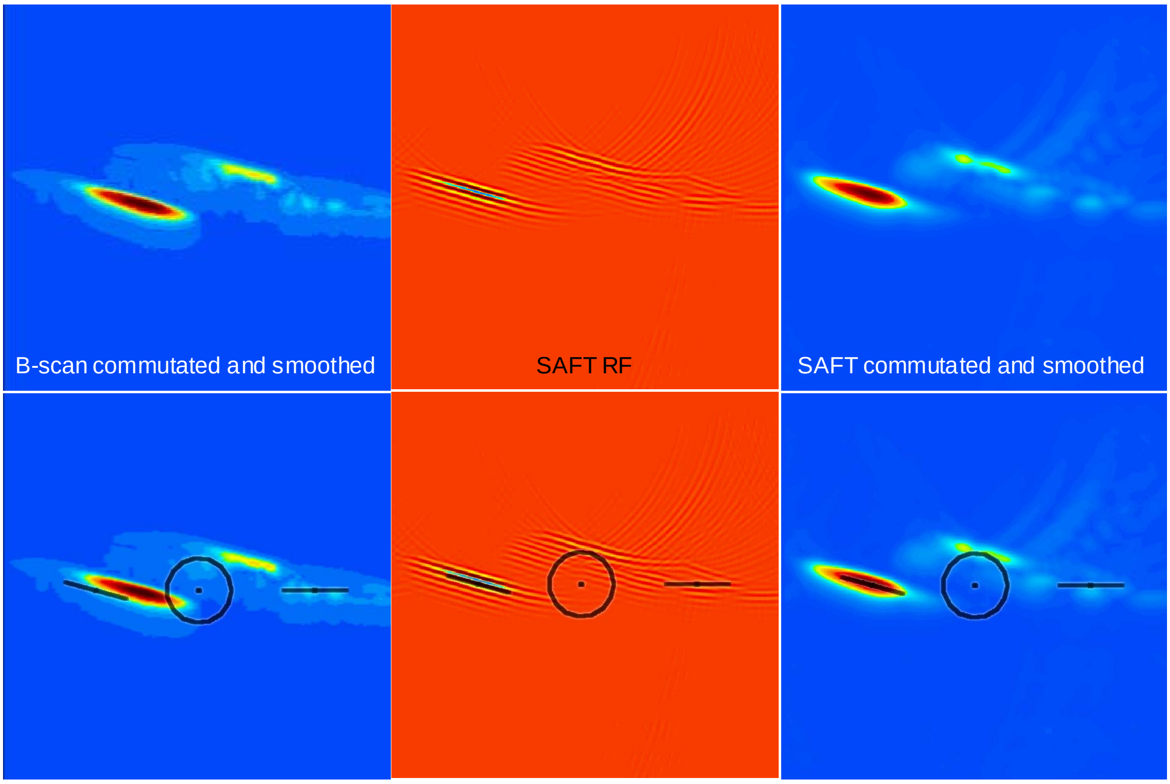

Fig. 9 SAFT-reconstruction and B-scan with pulse-echo signals of a normal sized probe, = 15°

Figures 8 and 9 illustrate what happens, if only one probe is used with a usual crystal size of e.g. 17.5 mm. Wave fronts appear in the SAFT-reconstruction generated by every reflective surface. The wave fronts corresponds in the size of the crystal and they are vertically oriented to the direction of incidence ($\alpha = 0°$ in figure 8 and $\alpha = 15°$ in figure 9). The rectangles are not mapped which are oblique to the direction of incidence. It's only possible to recognize the "crack tip" echoes. It is clear that a probe can only receive echoes within its own aperture.

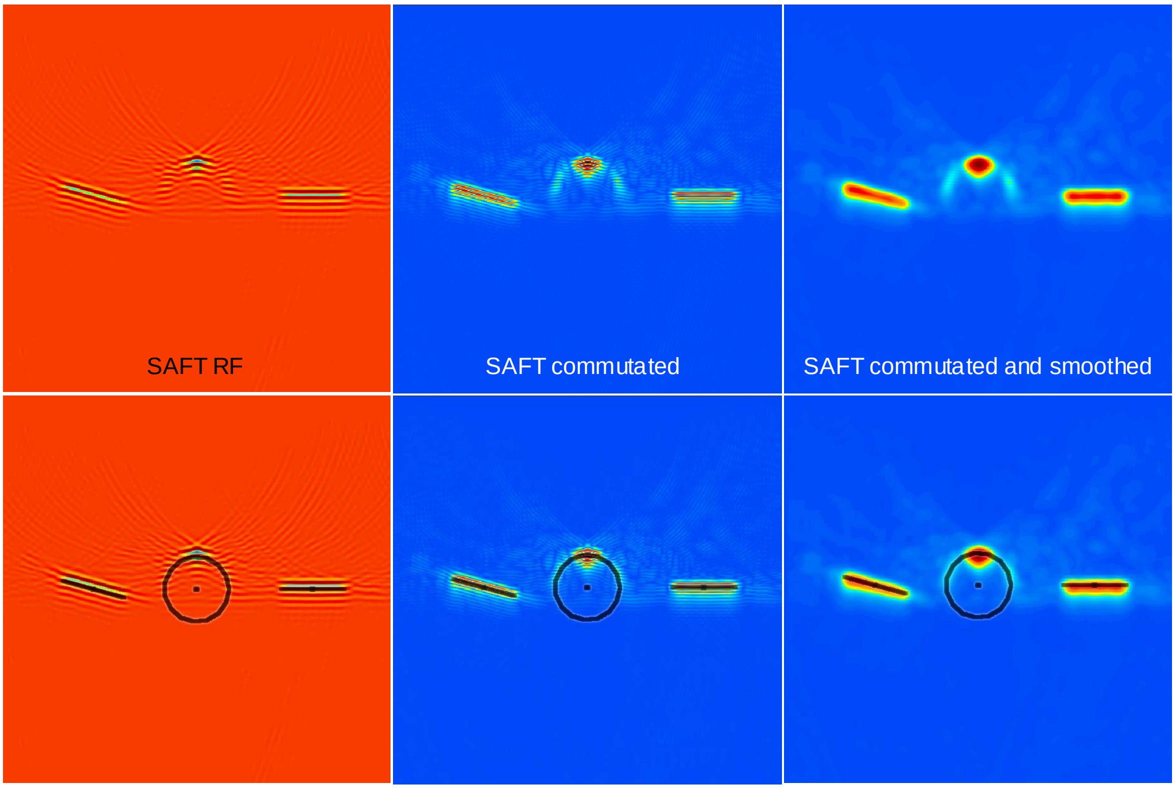

Fig. 10 SAFT-reconstruction with pulse-echo signals of a normal sized phased array probe using angles of incidence from – 25° to 25° in steps of 5°

A phased array probe is used in figure 10 which is 17.5 mm in size in the plane of incidence. The sound beam can be skewed at a large interval angle which is the same size as the divergence of a single element of the phased array probe. The same aperture can be realized by using only one element or by using the whole phased array probe skewing the beam in steps small enough to overlap the beams for each angle of incidence without gaps occuring. In this case the angle of incidence was skewed from -25° to +25° in steps of 5° at each probe position and all echo information was evaluated using the SAFT-algorithm. The images generated are similar to those obtained using the small probe (see figure 7).

"Images and mirror images" by reflection on the back wall with angle beam testing

Cracks starting at surfaces are an important type of flaw. They are mostly oriented in a vertical direction close to the surface often caused by the mechanical tensions. These flaws can be detected very sensitively with transversal wave angle beam testing using the so-called corner effect. Nevertheless, a statement about the depth of the crack is difficult.

The presence of a back wall has consequences on the detection and representation of reflectors in general which will be demonstrated in the following examples. This parameters stay the same: Angle beam testing with transversal waves in steel, centre frequency f = 1.5 MHz, λ = 2.2 mm, crystal size 20 mm in the plane of incidence, angle of incidence between 30° and 55°, divergence about 7° (-6dB), sound path is approx. 200 mm, dimension of each picture area is 60 x 60 mm^2.

In the B-scan in figure 11 an indication of the point reflector which corresponds to the expansion of the sound beam is observed. The effective aperture can also be increased by variation of the angle of incidence with angle beam testing, so that the SAFT-reconstruction reaches a considerably higher resolution.

Additional echo announcements originate from the back wall reflection. Their localization is defined by the direction and sound path similar to the direct flaw echo. Therefore, a mirror image originates behind the back wall (the blue sound path illustrated left in figure 12) and an additional echo that originates from the triangular path (the red path in figure 12). This echo is always located on the back wall, independent of distance of the reflector from the back wall (see also the figures 13 and 14).

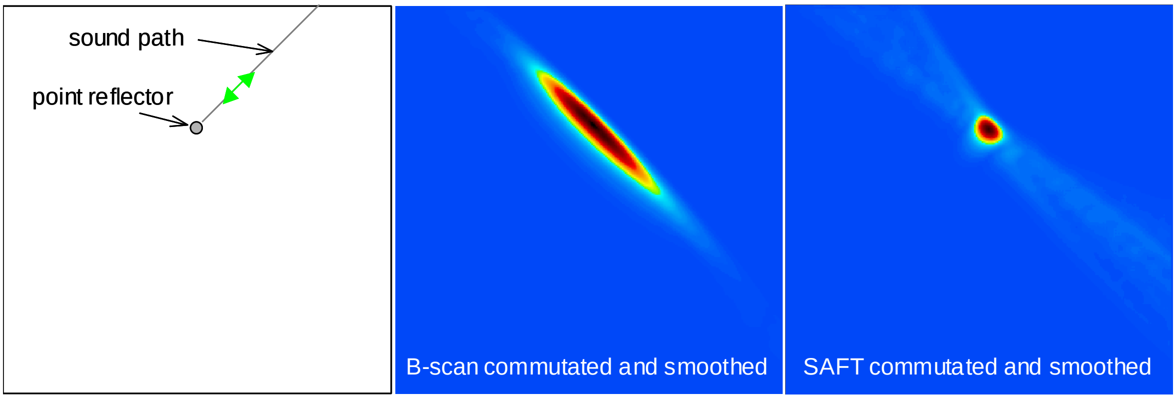

Fig. 11 reflector position, B-scan with 45° probe and SAFT-reconstruction using angles of incidence from 30° to 55° in steps of 5°

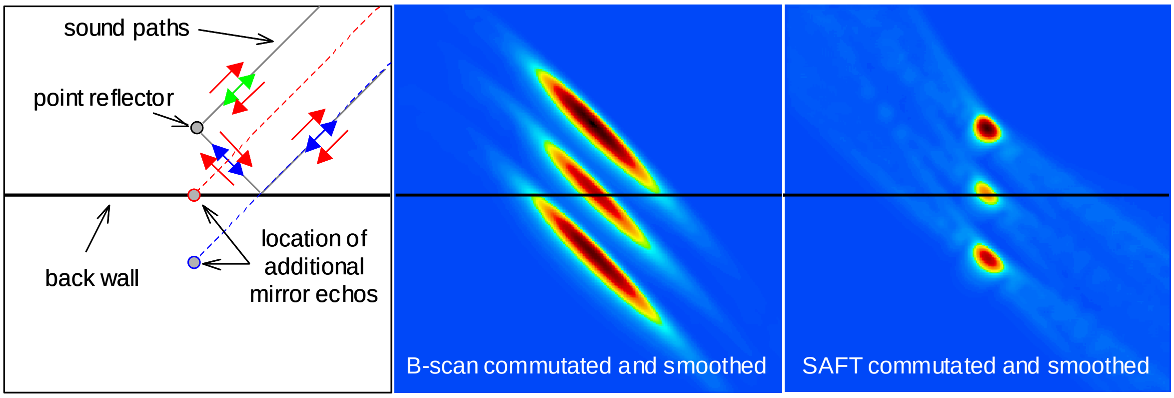

Fig 12 additional echos if a back wall is present, reflector position, B-scan and SAFT-reconstruction like figure 11

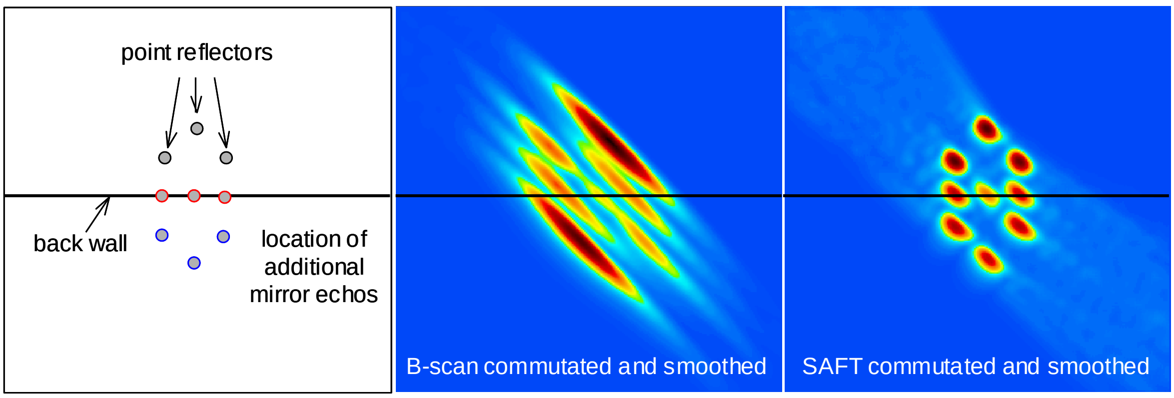

Fig. 13 reflector positions, B-scan with 45° probe and SAFT-reconstruction using angles of incidence from 30° to 55° in steps of 5°

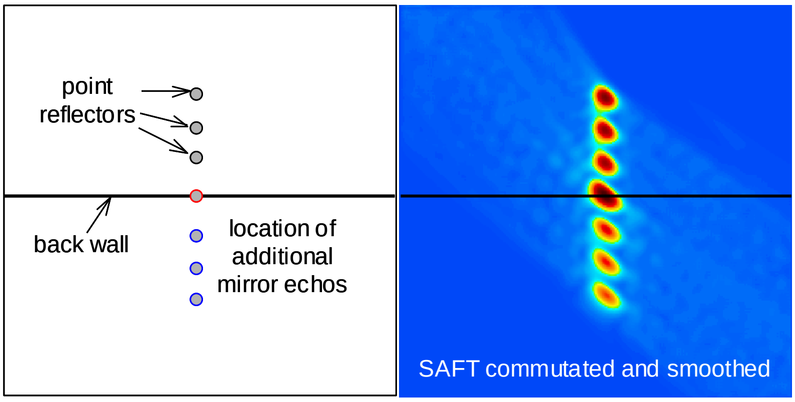

Fig. 14 reflector positions, SAFT-reconstruction using angles from 30° to 55° in steps of 5°

In the figures 13 and 14 the echoes of three point reflectors are indicated together. In figure 13 the B-scan can no longer be interpreted as a result of poor resolution. In the SAFT-reconstruction all indications are separated from each other. The indications of the triangular paths collapse locally and add up, if the reflectors lye in a line vertical to the back wall (figure 14). This is the reason, why a notch-like crack generates a strong echo that is localized on the back wall (figure 15). This is the corner mirror echo.

The surface of the crack reflects no sound directly back to the probe and, therefore, no image is generated from the surface! The diffraction echo from the upper crack end returns to the probe directly and can be localized. If this echo is large enough and can be seen, it's distance from the back wall can be interpreted as the depth of the crack. Whether a given picture is an indication of a surface crack or not, is hard to decide under these circumstances.

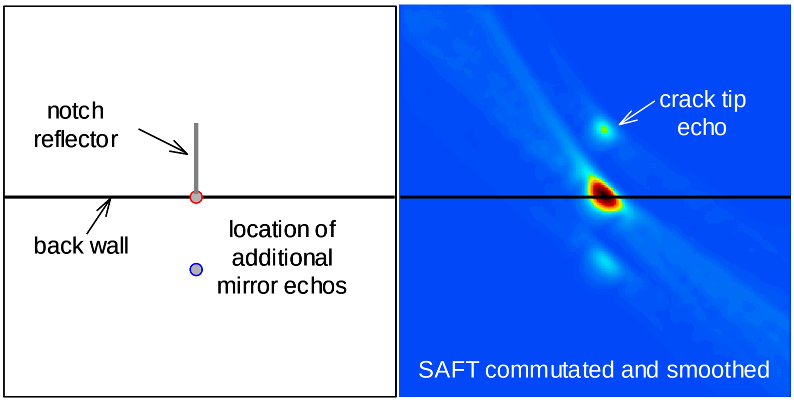

Fig. 15 notch reflector, SAFT-reconstruction using angles from 30° to 55° in steps of 5°

A plane flaw inside the material can generate a qualitatively similar picture, if its sloping position leads to the effect, that the direct echo is weakened in proportion to triangular echo (figure 16).

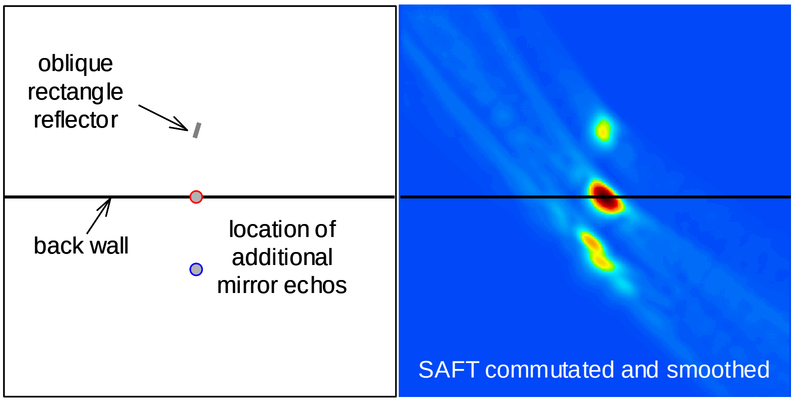

Fig. 16 oblique rectangle reflector, SAFT-reconstruction like figure 15

Conclusion

Evaluation procedures are often used, which generate picture-like representations to realize fast analysis of results, in particular in the automated ultrasonic testing. This results in large amounts of data. In this paper some simple examples were shown on how to obtain helpful images on the basis of simulated data and which difficulties are to be overcome. The flexibility of the phased array technique enables its use as a conventional detection technique and thereafter, if necessary, to realize an analysis using the whole aperture of the phased array probe to reach a good resolution with a SAFT-reconstruction. This provides an excellent compromise between economic testing constraints and high resolution when required with the same hardware. This was shown with simulated sound fields.

The SAFT-reconstruction provides a good image of the flaw, whenever direct reflections from the flaw surfaces are received. In other cases the surface of the flaw can not be seen in the SAFT-reconstruction and the result is equivocal, as demonstrated with the SAFT-reconstruction of a surface crack. The evaluation can often be complicated in practice by multiple reflections echoes or wave mode conversions, which were not discussed here. Nevertheless, an improvement of the resolution is achieved which is an advantage in all cases.